SF 298 MASTER COPY KEEP THIS COPY FOR REPRODUCTION PURPOSES

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
5/11/97

3. REPORT TYPE AND DATES COVERED
Final Technical 15 Dec 93 - 14 Mar 97

4. TITLE AND SUBTITLE
Novel Multiplexing Techniques for High-Speed Optical Transmission Systems Using Optical Amplifiers

5. FUNDING NUMBERS
61103D
A546/21

6. AUTHOR(S)
M.A. Ali
S.A. Ahmed
L. Roytman

AFOSR-TR-97
0160

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)
The City College of C.U.N.Y.
138th Street and Convent Avenue
New York, NY 10031

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NE
110 Duncan Ave., Suite B115
Bolling AFB, DC 20332-0001

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
F49620-94-1-0011

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

19970602 036

13. ABSTRACT *(Maximum 200 words)*

This report summarizes the work carried out during the period 10/15/93-3/15/97 and its significant accomplishments. The first part of the report discusses both theoretical and experimental achievements in proposed unidirectional and bi-directional self-healing inter-office WDM ring networks. Two different WDM schemes of self healing ring architectures were considered: 2-fiber unidirectional rings and 4-fiber bi-directional rings. Both types of ring networks are themselves completely survivable. The second part deals with the development of critical components required for the implementation of proposed OTDM network architecture. Specifically it examines switching characteristics of SOAs when used for external modulation and demultiplexing at both transmitter and receiver ends of a multi-Gb/s OTDM system. The third part of the report describes the overall progress achieved regarding the use of SOAs as external analog modulators to replace the use of semiconductor laser diodes otherwise required for direct modulation at the transmitter end of AM-VSB SCM CATV systems.

14. SUBJECT TERMS
Optical Multiplexing, Optical Transmission, Optical Networking

15. NUMBER IF PAGES
11

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500 DTIC QUALITY INSPECTED 1 Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

FINAL TECHNICAL REPORT

I. EXECUTIVE SUMMARY

Principal Investigators:
Profs. M. A. Ali, S. A. Ahmed, and L. Roytman
Department of Electrical Engineering
The City College of New York, N. Y., N. Y. 10031.

Grant Number: F49620-94-1-0011

Report period: 10/15/93-03/15/97

Title: "Novel Multiplexing Techniques for High-Speed Optical Transmission systems Using Optical Amplifiers"

People Involved In the Research Effort
Faculty: Profs. M. A. Ali, S. A. Ahmed, and L. Roytman

Industrial Collaborators: Drs. R. E. Wagner, R. Vodhanel, Janet Jackel (Bellcore, Red Bank, NJ). Drs. J. Zyskind, Y. Sun, J. Sulhoff, and Kazem Sohraby (Lucent Technologies, Bell Labs, Holmdel NJ), and Dr. J. Nagel (AT&T Research Lab, Holmdel, NJ).

Students: 3 Undergraduates and 8 Graduate Students.

Ph. D. Student Dissertations Completed Under This Research Effort

1. G. Mativieur, completed his Ph. D. (Feb. 1997) with dissertation entitled "Novel Hybrid CATV Network Architectures for Subcarrier Multiplexed Entertainment Video and B-ISDN Services in the Local Loop".
- He is currently employed with the Network Architecture Certification group as a Member of Technical Staff.
  AT & T, Crawfords Corner Road, Holmdel, NJ 07733.

2. J. Pan, completed his Ph. D. (Feb. 1997) with dissertation entitled "Detailed Performance Analysis and Feasibility Assessment of Self-Healing Local-Exchange Ring Networks Based on WDM Technology,"
- He is currently employed with the Optical Networking Group as a Member of Technical Staff.
  Nokia Research Center, Burlington, MA 01803.

3. F. Shehadi, completed her Ph. D. (Feb. 1997) with dissertation entitled "Survivable and Scalable Multiwavelength Ring Network Architectures for Broad-band Fiber Optic Networks: An Experimental Demonstration,"
- She is currently employed with the Hardware Integration group as a Member of Technical Staff.
  Bell Laboratories, Lucent Technologies, Crawford Corner Road,
  Holmdel, NJ 07733.

4. H. Issa, completed her Ph. D. (May 1996) with dissertation entitled "Long-Haul Very High Bit Rate Transmission Systems & All Optical Synchronous Multi-Access Fiber-Based Networks Using OTDM Technology and Optical Amplifiers,"

- She is currently employed with the Transport Node Planning group as a Member of Technical Staff, AT & T, Crawfords Corner Road, Holmdel, NJ 07733.

5. A. Hussien, completed his Ph. D. (March 1997) with dissertation entitled " Performance Analysis of a 2-D Multiserver Discrete-Time Queueing System with Correlated Batch Arrivals for ATM Based B- ISDN,"

- He is currently employed with the Transport Node Planning group as a Member of Technical Staff, AT & T, Crawfords Corner Road, Holmdel, NJ 07733.

6. G. Luo, completed his Ph. D. (May 1997) with dissertation entitled "Theoretical and Experimental investigations of all Optical Gain control in Multi-Channel EDFA Cascades and its implication on WDM Multi-Access Lightwave Networks Performance,"

- He is currently employed with the Network Architecture Certification group as a Member of Technical Staff, AT & T, Crawfords Corner Road, Holmdel, NJ 07733.

7. N. Khrias, completed his Ph. D. (May 96) with dissertation entitled "performance degradations due to laser and optical-filter misalignment in WDM systems,"

- He is currently employed with the Network Wireless Systems group as a Member of Technical Staff, Bell Laboratories, Lucent Technologies, Whippany, NJ 07081.

***A copy of these dissertations can be obtained from City University Graduate Center, 33 West 42nd street, New York, NY 10301.**

Publications Stemming From The Research Effort

[1] J. Pan, R. Vodhanel, S. Habiby, R. E. Wagner, A. Elrefaie, and M. A. Ali "A simple and robust method of gain equalization for the protection path of WDM self-healing ring networks," Optical Fiber Communication Conference (OFC'97), Technical digest series, Vol. 6, paper WL44, Dallas, Texas, Feb. 1997.

[2] G. Luo, J. Zyskind, Y. Sun, J. Sulhoff, and M. A. Ali "Relaxation oscillations and spectral hole burning in laser automatic gain control of EDFAs," OFC'97, Technical digest series, Vol. 6, paper WF4, Dallas, Texas, Feb. 1997.

[3] G. Luo, J. Zyskind, Y. Sun, J. Sulhoff, and M. A. Ali "Performance degradation of all-optical gain-clamped EDFAs due to relaxation oscillations and spectral hole burning in amplified WDM networks," Accepted for publication, IEEE Photonic Technology Letters, Vol. 9, 1997.

[4] Janet Jackel and D. Richards, "All-optical stabilization of cascaded multi-channel EDFAs with changing number of channels," OFC'97, Technical digest series, Vol. 6, paper TuP4, Dallas, Texas, Feb. 1997.

[5] Janet Jackel and D. Richards, "All-optical stabilization of multi-wavelength EDFA chains: a network-level approach", LEOS'96, Post-Deadline paper, Boston, MA.

[6] F. Shehadeh, T. Suzaki, and R. Vodhanel "Impact of external modulator chirp for 10-Gb/s transmission in an eight-wavelength eight-node WDM ring networks," OFC'97, Technical digest series, Vol. 6, paper TuE4, Dallas, Texas, Feb. 1997.

[7] F. Shehadeh, R. Vodhanel, and M. A. Ali "Comparison of gain control techniques to stabilize EDFAs for WDM networks," OFC'96, Technical digest series, Vol. 8, paper WM8, San Jose, CA, Feb. 1996.

[8] F. Shehadeh, R. Vodhanel, R. E. Wagner, and M. A. Ali, "Eight-wavelength WDM Add-Drop Multiplexer gain equalization," OFC'95, Technical digest series, Vol. 8, paper TuH2, San Diego, CA, Feb. 1995.

[9] F. Shehadeh, R. Vodhanel, R. Wagner, and M. A. Ali, "Gain-equalized, Eight wavelength WDM optical Add-Drop Multiplexer with an 8-dB dynamic range," IEEE Photonic Technology Letters, Vol. 7, PP. 1075-1077, Sep. 1995.

[10] N. Khrais, F. Shehadeh, R. Vodhanel, and R. E. Wagner, "Multiplexer eye-closure penalties for 10 Gb/s signals in WDM networks," OFC'96, Technical digest series, Vol. 8, Post-Deadline paper (PD33-2), San Jose, CA, Feb. 1996.

[11] R. Vodhanel, F. Shehadeh, G. Chang, and T. Suzaki, "performance of an 8-wavelength 8-node WDM ring network experiment with 80 Gb/s capacity," OFC'96, Technical digest series, Vol. 8, Post-Deadline paper (PD28-2), San Jose, CA, Feb. 1996.

[12] J. Pan, Ph. D. thesis (Feb. 1997), "detailed Performance Analysis and Feasibility Assessment of Self-Healing Local-Exchange Ring Networks Based on WDM Technology," City University Graduate Center, 33 West 42nd street, New York, NY 10301.

[13] Fatimah Shehadi, Ph. D. thesis (Feb. 1997) "Survivable and Scalable Multiwavelength Ring Network Architectures for Broad-band Fiber Optic Networks: An Experimental Demonstration," City University Graduate Center, 33 West 42nd street, New York, NY 10301.

[14] N. Khrais, A. Elerefaie, and R. E. Wagner and S. Ahmed, "Effect of cascaded misaligned optical (de)multiplexer on multiwavelength optical network performance," OFC'96, Technical digest series, Vol. 8, paper ThD4, San Jose, CA, Feb. 1996.

[15] N. Khrais, A. Elerefaie, R. Wagner and S. Ahmed, "performance degradation of multiwavelength optical networks due to laser and (De) multiplexer misalignments," IEEE Photonic Technology Letters, Vol. 7, pp. 1348-1350, Nov. 1995.

[16] N. Khrais, A. Elerefaie, R. E. Wagner, and S. Ahmed, "performance degradation in multiwavelength optical networks due to laser and (De) multiplexer misalignments," IEE, Electronics letters, July 1995.

[17] A. Elrefaie, M. A. Ali, R. E. Wagner, and F. Mendez "Fiber-amplifier Cascades in 4-fiber Multiwavelength Interoffice Ring Networks," Proceedings of the IEEE/LEOS Summer Topical Meeting on Optical Networks and their enabling technologies, Session T1.3, PP. 31-32, Lake Tahoe, NV, July 1994.

[18] M. A. Ali, A. Elrefaie, R. E. Wagner, F. Mendez, J. Pan, and S. Ahmed "Optimized performance of EDFAs in Multiwavelength lightwave Systems," IEEE Photon. Techn. Letters , Vol. 6, PP. 1039-1042, Aug. 1994.

[19] J. Pan, M. A. Ali, A. Elrefaie, and R. Wagner, "Multiwavelength Fiber-Amplifier Cascades with Equalization employing Mach-Zehnder optical filter," IEEE Photonic Techn. Letters, Vol. 7, PP. 1501-1503, Dec. 1995.

[20] J. Pan, A. Elrefaie, R. E. Wagner, and M. A. Ali "Fiber-amplifier Cascades with Equalization employing Mach-Zehnder optical filters in Multiwavelength Systems," Topical Meeting in Optical Amplifiers and their applications, paper FA3 PP. 114-116, Brecknridghe, Colorado, 1994.

[21] M. A. Ali, A. Elrefaie, R. Wagner, and S. Ahmed "Performance of EDFA Cascades in WDM Multiple access Lightwave Networks," IEEE Photonic Technology Letters, Vol. 6, PP. 1142-1145, Sep. 1994.

[22] M. A. Ali, A. Elrefaie, and R. Wagner, **(Invited)**, "980-nm versus 1480-nm pumped EDFA cascade performance in WDM multiple access Lightwave networks," Proceedings of the 8th IEEE/LEOS Annual meeting on Optical Networks and Systems (LEOS'95), Session ONS1.3, San Francisco, CA, October 1995.

[23] M. A. Ali, R. Wagner, A. Elrefaie, and S. Ahmed "A detailed comparison of the overall performance of 980- and 1480-nm pumped EDFA cascades in WDM multiple access Lightwave networks," Joint Special issue on Multiwavelength Optical Networks, IEEE Journals of Selected Areas in Commun./Lightwave Technology, Vol. 14, PP. 1436-1448, June 1996.

[24] D. Richards, M. A. Ali, and Janet Jackel, "EDFA chain control: A comparison of two all-optical approaches," Proceedings of the IEEE/LEOS Summer Topical Meeting on Technologies for a Global Information Infrastructure, Montreal, Canada, Aug. 1997.

[25] M. A. Ali, A. Elrefaei and S.A. Ahmed, "Simulation of 12.5 Gbit/s Optical Time Division Multiplexer using Semiconductor Optical Amplifiers as External Modulators," IEEE Photonic Technology Letters, Vol. 4, pp. 280-283, March 1992.

[26] M. A. Ali **(Invited),** "Semiconductor Optical Amplifiers for use in future B-ISDN," OF'93, Workshop on simulation and modeling of lightwave systems, San Jose, CA, Feb. 1993.

[27] M. A. Ali, and S.A. Ahmed "Simulation of Semiconductor Optical Amplifier for external modulation and demultiplexing in multi-Gb/s OTDM systems," International Conf. on lasers 91, Proceedings, Session WD.7, 1992.

[28] M. A. Ali, A. Elrefaei, H. Issa, and S. Ahmed, "High Speed Optical Time-Division Demultiplexer using Semiconductor Optical Amplifiers," IEEE Journal of Lightwave Technology, Vol. 10, pp 1735-1742. Nov. 1993.

[29] Hanna Issa, Ph. D. thesis (May 1996), "Long-Haul Very High Bit Rate Transmission Systems & All Optical Synchronous Multi-Access Fiber-Based Networks Using OTDM Technology and Optical Amplifiers," City University Graduate Center, 33 West 42nd street, New York, NY 10301.

[30] G. Mativieur and M. A. Ali, "Simulation of multi-channel AM-VSB CATV optical link employing Semiconductor Optical Amplifier as an external modulator," IEEE Photonic Technology Letters, Vol. 8, PP. 122-124, Jan. 1996.

[31] G. Mativieur and M. A. Ali "Simulation of multi-channel AM-VSB CATV lihgtwave system employing SOA as an external modulator," Proceedings of the 8th IEEE/LEOS Annual meeting on Optical Networks and Systems (LEOS'95), session OC8.2, San Francisco, CA, Nov. 1995.

[32] M. A. Ali and G. Mativieur, "Performance analysis of multi-channel 16/64-QAM CATV distribution network using Semiconductor Optical Amplifier as an external modulator," IEEE Photonic Technology Letters , Vol. 9, pp. 690-692, May 1997.

[33] G. Mativieur and M. A. Ali "Simulation of multi-channel 16/64 QAM CATV distribution network employing SOA as an external modulator," Proceedings of the 9th IEEE/LEOS Annual meeting on Optical Networks and Systems (LEOS'96), Session OC8.2, Boston., MA, Nov. 1996.

[34] G. Mativieur, Ph. D. thesis (Feb. 1997), "Novel Hybrid CATV Network Architectures for Subcarrier Multiplexed Entertainment Video and B-ISDN Services in the Local Loop," City University Graduate Center, 33 West 42nd street, New York, NY 10301.

II. STATEMENT OF WORK

The above referenced project seeks, through computer simulation and modeling, to more effectively exploit the enormous inherent bandwidths of optical fibers by combining them with the tremendous potential functional capability of both semiconductor optical amplifiers (SOAs) and Erbium-doped fiber amplifiers (EDFAs). It focuses on developing novel schemes for: (I) wavelength-division multiplexing (WDM); (II) optical time-division multiplexing (OTDM); and (III) subcarrier multiplexing (SCM) for use in ultra high-speed transmission systems and multi-access optical networks.

III. Technical Summary

This report summarizes the work carried out during the period 10/15/93-03/15/97 and its significant accomplishments. The first part of the report discusses both theoretical and experimental achievements in proposed uni-directional and bi-directional self-healing inter-office WDM ring networks. Two different WDM schemes of self healing ring architectures were considered: 2-fiber unidirectional rings and 4-fiber bi-directional rings. Both types of ring networks are themselves completely survivable. The second part deals with the development of critical components required for the implementation of proposed OTDM network architecture. Specifically it examines switching characteristics of SOAs when used for external modulation and demultiplexing at both transmitter and receiver ends of a multi-Gb/s OTDM system. The third part of the report describes the overall progress achieved regarding the use of SOAs as external analog modulators to replace the use of semiconductor laser diodes otherwise required for direct modulation at the transmitter end of AM-VSB SCM CATV systems.

IV. SIGNIFICANT WORK ACCOMPLISHED

IV.1 WDM Scheme:

Given the recognized topical importance of WDM technology in priorities for the establishment of cost effective national optical networks, most of our research efforts have focused on WDM scheme. Specifically, this part of the work has focused on examining the technological requirements and assessing the performance analysis and feasibility for implementing self-healing inter-office ring (SHR) networks that utilize commercially available WDM technology, all-optical Add/Drop multiplexers, all-optical protection ring using Erbium-doped Fiber Amplifiers, and optical switches to provide survivable transport in the local-exchange network layer. Two different WDM schemes of self healing ring architectures were considered: 2-fiber unidirectional rings and 4-fiber bi-directional rings. This part of the work has been being carried out in two overlapping phases: (i) modeling and simulation, and (ii) related experiments.

i. Experimental Accomplishments

The experiments were carried out in Bellcore labs (Red Bank, NJ) and Lucent Technologies, Bell Labs (Holmdel, NJ), with the collaboration of Dr. R. E. Wagner, Dr. R. Vodhanel, Dr. Janet Jackel, Dr. J. Zyskind, and Dr. J. Nagel and the participation of seven of our Ph. D. students.

The following summarizes the significant experimental accomplishments:

- We have experimentally examined and analyzed the performance of all the critical elements necessary for the implementation of high–capacity, scalable, and survivable WDM SHR networks [1-11]; specifically:

- We have successfully demonstrated a simple and robust method of gain equalization for the protection path of survivable self-healing rings employing MZ filters. This method can bring the gain variations from 12 dB to < 4 dB for a six-nodes SHR or from 18 dB to < 6 dB for a nine-nodes SHR [1].

- We have considered the applicability of laser Automatic gain control (AGC) to control fast power transients in WDM optical networks and have reported the first high resolution measurements of transients in such gain controlled EDFA's [2-3]. It was shown that these power excursions have two contributions: a static contribution owing to the spectral hole burning (SHB), and a dynamic contribution owing to the relaxation oscillations in the laser. These effects were shown to be small but will compound in large networks of concatenated EDFAs in which laser AGC is employed in each EDFA and the performance of surviving channels may be impaired [2-3].

- We have devised and tested an all-optical feedback technique for stabilizing the per-channel output both for single amplifiers and cascades of amplifiers [4-5]. This technique is simple, inexpensive, and robust, requiring neither monitoring of the amplifier output nor any active feedback. One of the great virtues of this technique is that only the first in a chain of amplifiers need to be modified. We have demonstrated that stabilization occurs rapidly enough to satisfy what we believe are the realistic needs of any practical system.

- We have demonstrated the impact of external modulator chirp for 10-Gb/s transmission in an eight-wavelength eight-node WDM ring networks [6].

- Three techniques to stabilize the WDM output power of EDFA to within 0.1 dB were demonstrated by: 1) controlling the pump power, 2) adding a co-propagating control signal, 3) adding a counter-propagating control signal [7].

- We have successfully demonstrated a gain equalized eight wavelength WDM optical add-drop multiplexer over 8 dB dynamic range [8-9].

- We have demonstrated that both the magnitude and the phase of multiplexer and demultiplexer transfer functions are important in determining the distortion-induced penalties in WDM networks where multiplexers and demultiplexers are cascaded. The experimental results indicate that laser misalignment tolerances are determined by the effects of these distortion-induced penalties [10].

- We have constructed several laboratory testbed experiments designed to answer critical systems and technology questions, to demonstrate interworking of the network elements and subsystems, and to verify the technological feasibility of implementing the proposed WDM ring network architectures. Specifically, we have reported the successful transmission performance of an eight-wavelength, 8-node WDM ring network at 2.5 Gb/s and 10 Gb/s data rates per channel, giving total network capacities of 20 Gb/s and 80 Gb/s [11]. To the best of our knowledge, this is the largest WDM ring experiment with the highest capacity yet reported.

ii. Simulation and Modeling Accomplishments

The following summarizes the significant accomplishments:

- A flexible, powerful computer modeling tool was developed for evaluating the end-to-end performance of WDM ring network. The modeling tool included wavelength driven and time driven capabilities. The wavelength driven capability was required to model the effects of cascading many optical amplifiers, optical filters, and wavelength/space cross-connect switches on the output signal to noise ratio and crosstalk level of any wavelength on the network. The time driven capability was required to model the effects of fiber chromatic and polarization dispersion and fiber nonlinearity combined with source degradations, such as laser chirp and excess chirp in external modulators, on the signal quality at any wavelength in the network.

- Overall performance targets of the proposed 2-fiber and 4-fiber uni/ bi-directional self-healing WDM ring networks are defined and identified, covering topics of transparency, wavelength assignment, channel spacing, crosstalk, signal level and noise accumulation, transmission impairments and misalignment tolerances. Limits on optical amplifier cascades and WDM filters, device cross-talk impairments, nonlinearities, and dispersion were examined and determined [12-24].

- We have characterized and modeled the performance of several candidate WDM architectures, such as, ring, star, and mesh architectures from the point of view of architectural constraints associated with the number of wavelengths, the cascadability of optical amplifiers, and the crosstalk limitations [12-13].

- EDFA cascades using a simple gain equalization scheme employing demultiplexers with fixed attenuators were shown to be capable of supporting the working path for 16-office wavelength-routed unidirectional WDM ring networks [12]. The size and capacity limits of this type of uni-directional ring are imposed by the non-flat gain spectra of the fiber amplifiers. This constrains the number of wavelengths on the ring to approximately 15 assuming channels are spaced by 2-nm.

- EDFA cascades were shown capable of supporting the working path in bi-directional WDM ring networks employing 15 wavelengths and serving 11 offices without requiring gain equalization [12-13]. The accumulated SNR is sufficient for 10 Gb/s operation at each wavelength, allowing a network capacity of 550 Gb/s for a full mesh traffic pattern.

- 980-nm pumped EDFA cascades were shown capable of supporting 6-wavelength interoffice 4-fiber ring network with up to 7 offices, without requiring gain equalization, and while maintaining equal signal levels and adequate SNRs at all wavelengths throughout the network, independently of the network mode of operation [17].

- **Channel spacing considerations**

Four key issues that constrain the allowable channel spacing for the WDM ring network were identified: a) fiber nonlinearities; b) multiplexer cascade misalignment tolerances; c) crosstalk; and d) the nonuniform gain spectrum of EDFAs [12-22]. For long distance spans, optical nonlinearities were shown to set the channel spacing range to be somewhere between 100 and 275 GHz. Two types of fiber nonlinearities which set the lower and upper bounds on the allowed channel spacing were identified. The lower bound of 100 GHz is set by cross-phase modulation, caused by the optical Kerr effect. The upper bound of 275-GHz is set by stimulated Raman scattering, which causes channels at shorter wavelengths to act as pumps providing gain to channels at longer wavelengths. For short distance spans, where there are cascades of many optical filters (multiplexers and demultiplexers are filters), the misalignment and bandshape of the filters sets a lower bound on the channel spacing of about 250 GHz. Our simulation results have indicated that with two grating-based optical filters, laser misalignments of about 30 GHz for 25-GHz filter misalignments are found to produce a 1 dB system power penalty [14-16]. For a cascade of 20 uniformly misaligned optical filters, and a laser misalignment of 35-GHz, the filter passband must be at least 120 Ghz.

- **Channel assignment considerations**

The key issue that determine channel assignment are selection of the flattest region of a cascaded EDFA gain spectrum. Since the use of EDFA cascades represent the key technology which enables the realization of the proposed WDM ring networks, we have developed an understanding of the various technological difficulties which face EDFA cascades with multiwavelength handling capabilities. Two related fundamental problems have been addressed: (1) spectral gain non-uniformity, (2) “transient cross-saturation” or “gain dynamics". Two main objectives must be satisfied:

a) To ensure sufficient gain flatness to permit amplifiers to be cascaded while maintaining acceptable inter channel power variations and signal-to-noise ratios at all wavelengths.

b) To maintain constant per-channel output power with a minimally degraded SNR, regardless of the number of channels present. The basic requirement is that the quality of service for any given channel passing through an optical amplifier shall not be adversely impacted by anything that happens to any of other channels passing through the same amplifier.

What is needed is a gain-flattened and stabilized EDFA configurations for DWDM transmission systems. These EDFA configurations must be capable of satisfying the following:

- Low-noise and high output power.

- Gain flatness should be independent of the operating conditions (signal and pump power levels, etc.).
- Constant output-signal power over a wide dynamic range of input signal levels.

Two different approaches to equalize (flatten) the passband of cascaded EDFAs have been examined:

i) In the first approach, the initial objective was to simplify the practical implementation of the transfer function of the filter required to make the EDFA-filter combination have an output as flat as possible. This is achieved by optimizing the individual amplifier performance parameters for multiple wavelength operation [18]. Using this approach, the effectiveness of several passive equalization techniques have been examined to exploit the entire optical bandwidth of the amplifiers. The results of this approach showed effective gain equalization over most of the entire useful EDFA gain bandwidth [19-20].

ii) In the second approach, a simple optimization analysis was suggested to relate the individual amplifier performance parameters to the overall performance of an amplifier cascade for best overall system performance without having to resort to expensive external equalization methods. This work showed that 980-nm pumping, together with the optimum choice of the amplifier length, provides adequate performance for six 10 Gb/s WDM channels to be transmitted through a cascade of 27 amplifiers, allowing a total system gain of more than 350 dB without requiring gain equalization methods [21-23].

- We have developed a dynamic simulation tool for modeling the behavior of a single EDFA and amplifier chains, and have used it to model the behavior of these amplifiers with and without stabilization against gain changes due to changing numbers of channels. The main objective was to understand how nearly one can maintain constant per-channel output power with a minimally degraded SNR, regardless of the number of channels present. Using an amplifier designed to optimize gain and minimize gain variation when 8 channels are present, we have examined the factors that affect the transient power excursions in the surviving channel. We have also modeled and compared the behavior of two different approaches to chain stabilization. We highlighted the robustness of these approaches and also showed some of their limitations and advantages [24].

- We have shown how any degradation at the first EDFA has a cumulative effect at the output of all subsequent EDFA's in the chain. Specifically, we have shown that the lower the losses in the feedback loop, the slower the switching speeds and the smaller the numbers of dropped channels, the smaller the power excursions experienced by the surviving channel. Therefore, the switching speed at the network element, the loss in the feedback loop, and the choice of lasing wavelength at the first amplifier all determine the cumulative effect at the end of EDFA chain [24].

IV.2 OTDM Scheme:

In this part of the work we have developed a model of a novel optical time-division multiple-access (OTDMA) network architecture that relates parameters at the device-level to system-level performance measures such as bit error rate (BER) and noise margin. The simulation modeling is characterized by its consideration of the full potential for exploiting traveling wave semiconductor optical amplifiers (TWSOAs) as multifunction components in both long haul optical transmission systems and multiple-access broad-band fiber optic networks. Specifically, the nonlinear model is used to examine the switching characteristics of TWSOAs when used for external modulation and demultiplexing at both the transmitter and receiver ends of a multi-Gb/s OTDM system [25-29]. Employing TWSOAs as high-speed optical gates at both the transmitter and receiver ends of OTDM systems will, (i) provide simultaneous gain and gating, and hence increase both information capacity and transmission distance, and (ii) replace the present inherently bulky and lossy Ti: $LiNbO_3$ waveguide external modulators and demultiplexers, required at each end of each channel, with compact ones suitable for opto-electronic integrated circuit (OEIC) implementation. This approach may allow for lossless devices and future monolithic integration of external modulators with lasers and of demultiplexers with detectors or with opto-electronic integrated front-ends. Optical gating with TWSOAs is also of particular interest for bus or broadcast network architectures where one channel on a bus is sampled and access to all channels is required. We have developed computer simulation techniques to investigate and analyze the material and structure parameters of TWSOAs, and their effects on the overall performance of the proposed OTDM system, for which the switching speed, rather than the gain, is the ultimate function. Thus, in the basic form of the OTDM system proposed here, TWSOAs were configured as:

i) low chirp external modulators to replace the conventional bulky and lossy waveguide external modulators used exclusively in OTDM system transmitters. These, in addition to modulating the transmitted signal will also amplify it and eliminate the standard 3 dB losses associated with the use of conventional bulky and lossy Ti: $LiNbO_3$ waveguide external modulators in each channel. This approach results in an increase in both the total information capacity (more channels might be multiplexed) and transmission distance (overall power budget is also increased) of the system.

ii) high speed optical gates for optical demultiplexing to replace the conventional bulky and lossy waveguide demultiplexers used exclusively in OTDM system receivers. Once again, in addition to demultiplexing the received multiplexed signal and eliminating the usual losses otherwise associated with the use of conventional bulky and lossy Ti: $LiNbO_3$ waveguide demultiplexers, the received signal is also amplified. This results in improvement in the receiver sensitivity and overall increase in the SNR at the receiver.

The following summarizes the significant accomplishments:

- Using computer simulation techniques, we have developed a nonlinear model for the dynamic operation of both Zn doped and undoped active region TWSOAs. The model is used to investigate the performance of the amplifier, when used as an optical gate, as a function of the frequency and amplitude of the RF driving signal, the precise time delay between the incident optical signal and the driving electrical signal, and the input optical signal levels. Using these models, we have shown that present TWSOAs devices with an undoped active region (or unintentionally slightly doped) can be used as low chirp, external modulators and demultiplexers at modulation speeds of 2.5 Gb/s per channel and demultiplexing speeds as high as 12 Gbit/s [25-29].
- We have shown that maximum demultiplexing speed can be increased from the 6 Gb/s maximum speed achievable using a single TWSOA gate, to 10-12 Gb/s by using an optical gate consisting of two cascaded TWSOAs [28].

- We have also shown that maximum modulation speed can be increased from the 2.5 Gb/s per channel achievable using an undoped active region TWSOA gate, to 10 Gb/s per channel by using a Zn doped active region TWSOA gate and a raised-cosine waveform RF driving current [25-29].

- Satisfactory demultiplexing performance at 10 Gb/s can also be achieved using a single Zn-doped active layer TWSOA gate [28-29].

- Using TWSOAs as external modulators and demultiplexers at both the transmitter and receiver ends of the proposed multi-Gb/s OTDM system provides adequate overall system performance for eight 2.5 Gb/s channels transmitted over a transmission distance of about 300 Km [29].

IV.3 SCM Scheme:

As a natural extension of the above approach, we have also examined the potential of using TWSOAs in another potentially useful multiplexing technique: subcarrier multiplexed (SCM) lightwave systems, e. g., for CATV applications. Specifically, we have examined the use of TWSOAs as external analog modulators to replace the use of semiconductor laser diodes otherwise required for direct modulation at the transmitter end of AM-VSB SCM CATV systems [30-34].

The following summarizes the significant accomplishments:

- We have examined the current-power (I-P) characteristics of the amplifier over a wide dynamic range of both input optical power (-30 dBm-0 dBm) and driving current (0-200 mA). We were able to identify the dc operating point which yields the best I-P linearity [30-31].

- We have determined second and third order dynamic intermodulation distortions associated with the use of TWSOAs as external modulators for SCM systems. The simulation results have indicated that TWSOAs are potential candidates for use as external analog and digital modulators for SCM CATV systems [30-34].

- We have shown that by using a TWSOA as an analog external modulator, a system power budget of 17 dB is attained for a 42-channel AM-VSB CATV system within an octave of frequency range, from 300 to 546 MHz, while delivering a 50 dB CNR and less than - 60 dBc CTB distortion [30-31].

- It is shown numerically that by using a TWSOA as an external modulator at the transmitter end of a multi-channel 16/64-QAM optical CATV link, up to 400/600 MPEG2 video channels could be transmitted with a total link budget of 34/27 dB [32-33].

V. REFERENCES

See the subsection list of "publications stemming from the research effort", listed above in the executive summary. These publications are listed according to the sequence of the references listed in section IV.